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Stress concentration and fracture at inter-variant boundaries in an Al-Li alloy

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Delamination fracture has limited the use of lightweight Al-Li alloys. Studies of secondary, delamination cracks in alloy 2090, L-T fracture toughness samples showed grain boundary failure between variants of the brass texture component. Although the adjacent texture variants, designated Bs_1 and Bs_2, behave similarly during rolling, their plastic responses to mechanical tests can be quite different. EBSD data from through-thickness scans were used to generate Taylor factor maps. When a combined boundary normal and shear tensor was used in the calculation, the delaminating grains showed the greatest Taylor Factor differences of any grain pairs. Kernel Average Misorientation (KAM) maps also showed damage accumulation on one side of the interface. Both of these are consistent with poor slip accommodation from a crystallographically softer grain to a harder one. Transmission electron microscopy was used to confirm the EBSD observations and to show the role of slip bands in the development of large, interfacial stress concentrations.

Stress Concentration and Fracture at Inter-variant Boundaries in an Al-Li Alloy

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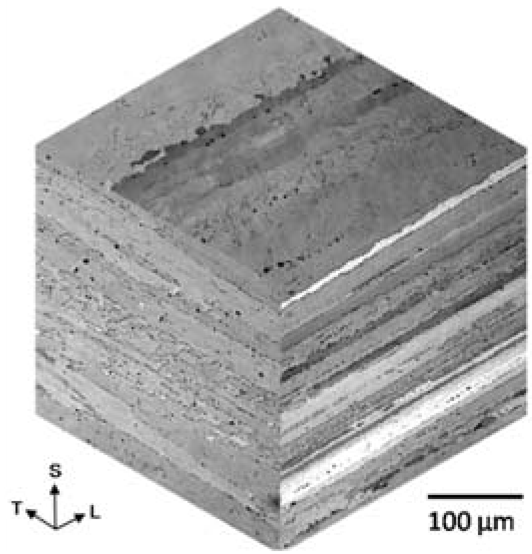
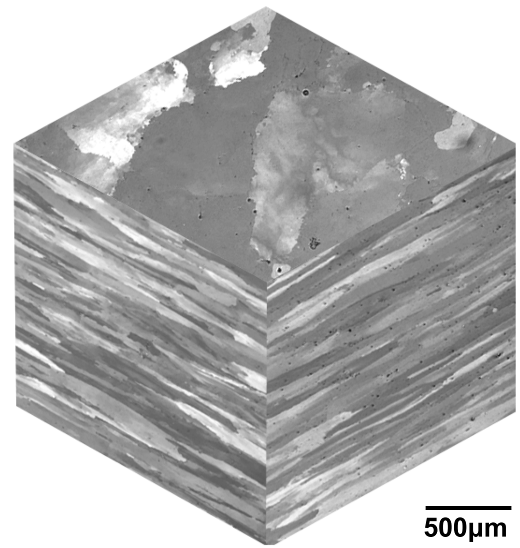
Synopsis

- Commercial Al-Li alloys, loaded in the rolling direction, exhibit delaminations parallel to the rolling plane
- Crystal Plasticity Models (UIUC) show delamination ahead of the primary crack, plastic anisotropy around delamination, normal-shear stress coupling under plane-stress conditions
- OIM-Fractography shows:
    - Fracture along Brass texture component inter-variant boundaries
        - Severe deformation in one grain, single slip system bands due to shear, stress concentration at interface
        - high Taylor Factor differences for normal-shear coupling
    - Fracture along Brass/Cube associated with crack tip blunting
    - Involvement of grain boundary precipitates

Al-Li Alloys 2090 and C458

Microstructure and Chemistry





2090 t/2

Long, flat grains

C458 t/8

Processed for less anisotropy, shows less grain flatness

Composition (%wt)

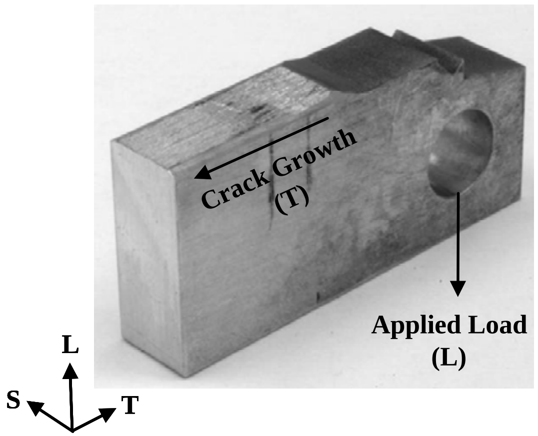
Alloy	Cu	Li	Zn	Mg	Mn	Zr
C458*	2.60	1.70	0.60	0.30	0.25	0.09
2090	2.35	2.30	0.10	0.25	0.05	0.10

*Aluminum Association designation 2099

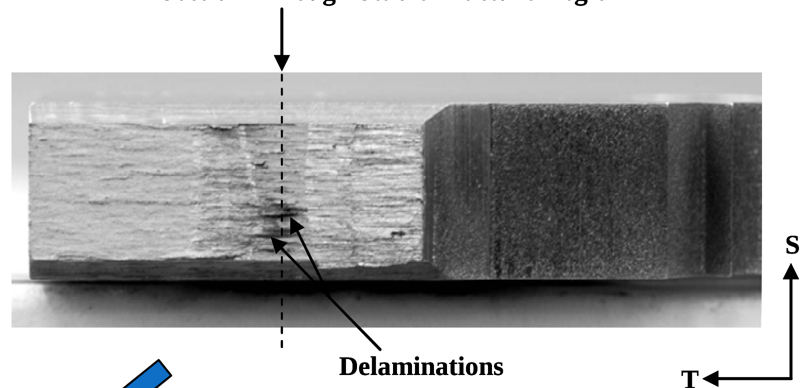
L-T Compact Tension Specimen
Crack-divider orientation of delaminations

Compact Tension Specimen

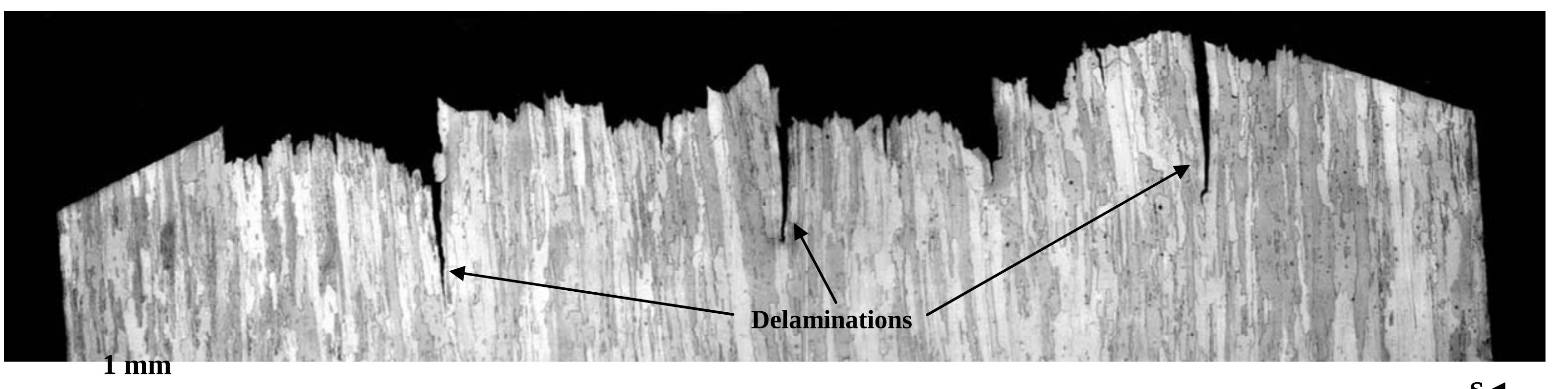
Half specimen; Post-failure



Section Through Stable Fracture Region



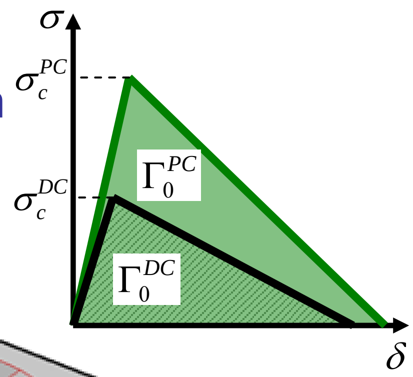
Metallurgical Section of L-S Plane

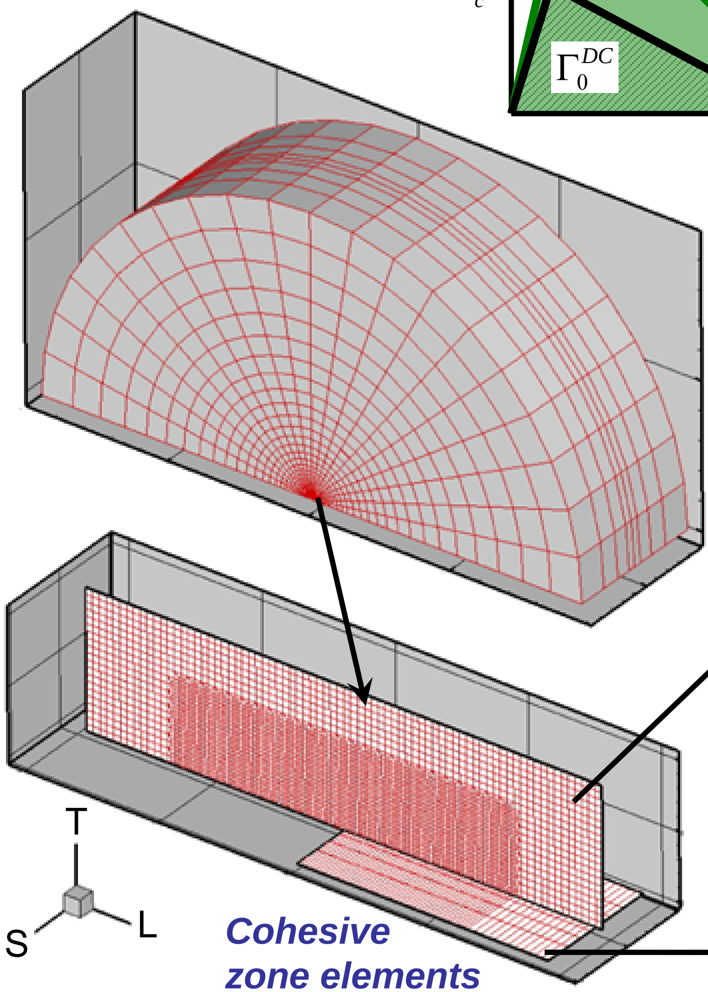


T-L Fracture

Crystal Plasticity Model with Cohesive Zone Elements (UIUC)

Bicrystal model with reduced delamination energy and strength



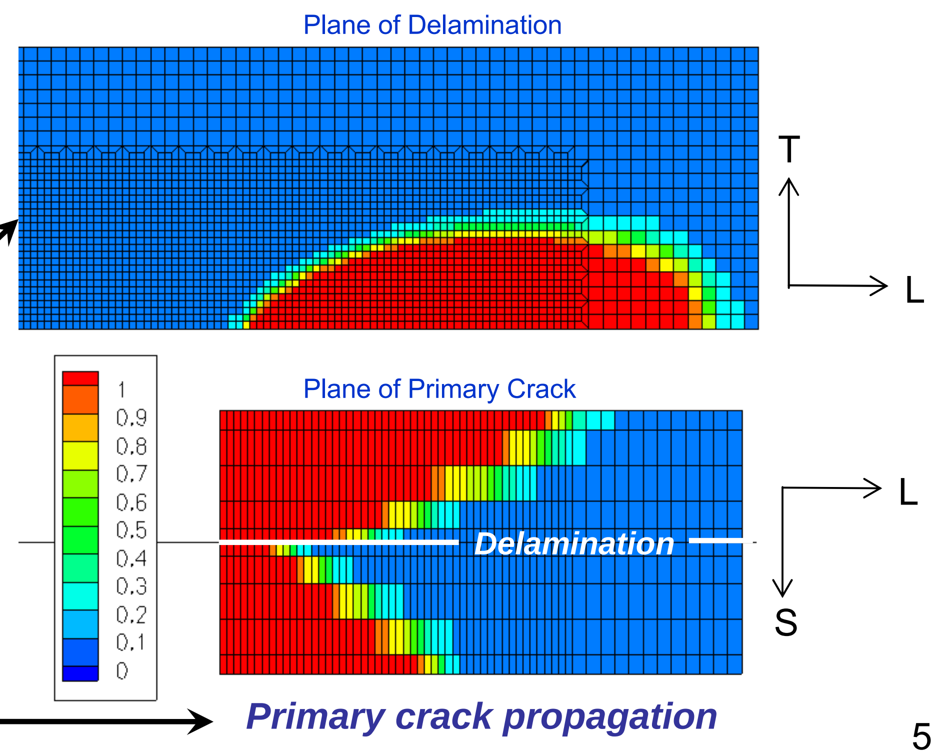


Delamination precedes primary crack

Primary crack grows asymmetrically

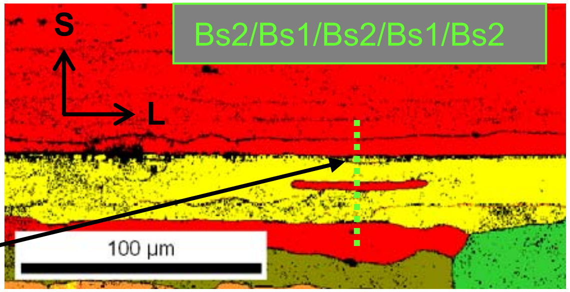
Significant **plastic anisotropy** for Bs1/(near)Bs2 interface

Normal-Shear stress coupling under plane-stress conditions *after* initiation

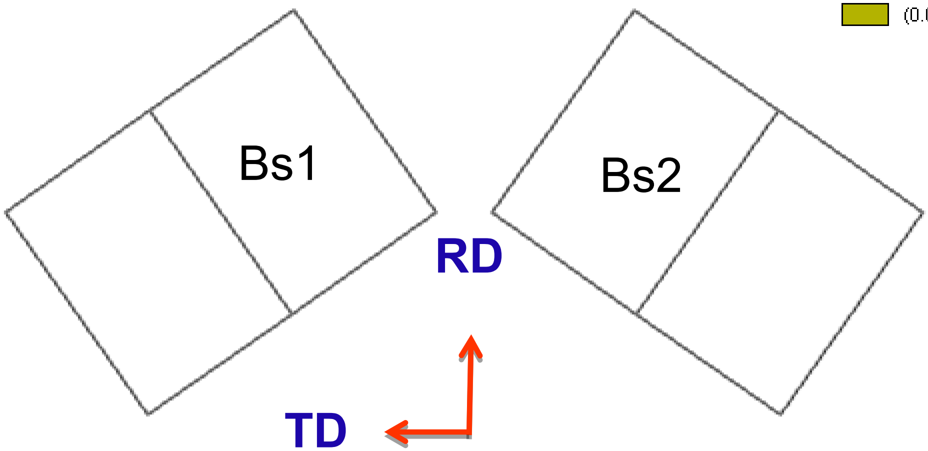


Inter-variant Boundaries in 2090 Al-Li

- Most delaminations occurred between variants of the **Brass** texture component, which are related by orthotropic sample symmetry, but not crystal symmetry. The delaminating boundaries tend to be flat and long.
- Brass has two variants: Bs1 and Bs2
  - Bs1 : (35, 45, 0) or (011)[2-11]
  - Bs2 : (55, 90, 45) or (110)[1-12]
  - Related by 180° rotation about <2-11> rolling axis (= 60°/<111> minimum misorientation)
  - **Frequently alternate Bs1/Bs2**
- Brass develops during hot rolling
- Dominant at mid-thickness of plate



Orientation Euler Angles	Orientation {hk(i)l}<uv(t)w>
(35.0, 45.0, 0.0)	(0 1 1)[2 -1 1]
(55.0, 90.0, 45.0)	(1 1 0)[1 -1 2]
(39.2, 65.9, 26.6)	(1 2 1)[1 -1 1]
(90.0, 35.0, 45.0)	(1 1 2)[-1 -1 1]
(0.0, 0.0, 0.0)	(0 0 1)[1 0 0]
(0.0, 45.0, 0.0)	(0 1 1)[1 0 0]
(0.0, 18.0, 0.0)	(0 9 28)[1 0 0]
(0.0, 72.0, 0.0)	(0 28 9)[1 0 0]



wire lattice sketch

Sample Preparation
Mechanical Polishing (only)

- Performed on a precision polishing apparatus
  - Calibrated to within $\pm$ 3μm tolerance

- Ability to control depth of material removal and polishing load

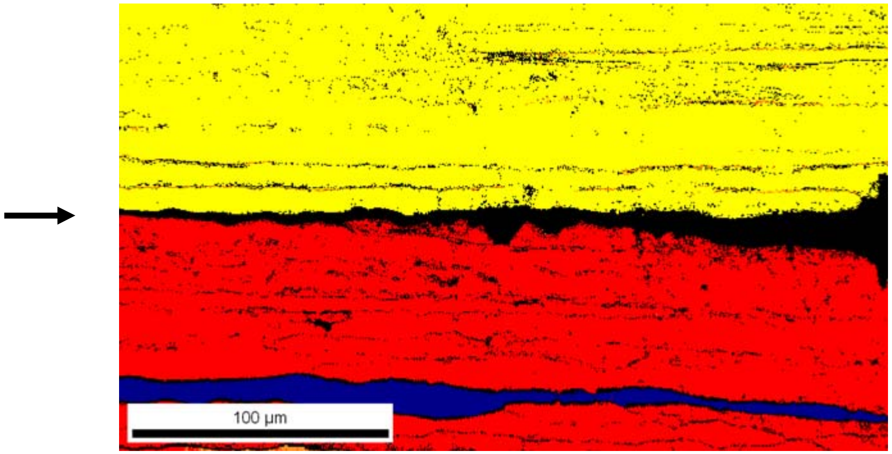
- Variable rotational speed and load controls

- Final polish for 1 hr with colloidal silica
  at 50 RPM and 100 gram load

- Produces relatively flat, strain free surfaces
  - EBSD hit rates > 90%
  - Deformed layer must be small, since EBSD pattern derives from 40 nm depth

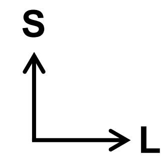
Grain Orientations at Delaminations in 2090

L-T Compact Tension Specimen



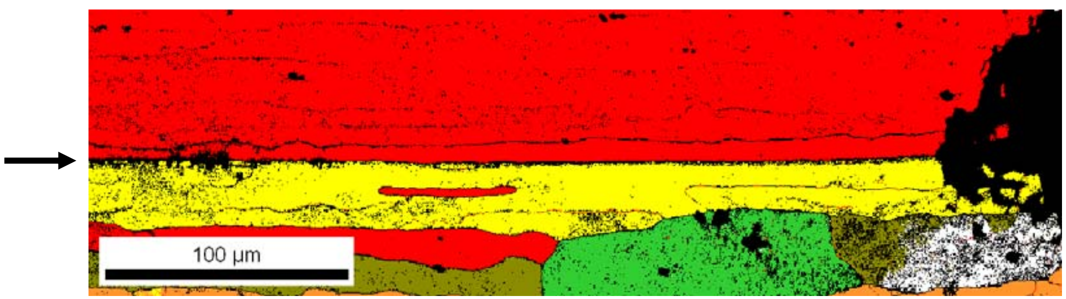
1.5 mm in length

Bordered by **Bs1/Bs2**



Delamination 1

	Orientation Euler Angles	Orientation {hk(i)l}<uv(t)w>
yellow	(35.0, 45.0, 0.0)	(0 1 1)[2 -1 1]
red	(55.0, 90.0, 45.0)	(1 1 0)[1 -1 2]
orange	(39.2, 65.9, 26.6)	(1 2 1)[1 -1 1]
light orange	(90.0, 35.0, 45.0)	(1 1 2)[-1 -1 1]
green	(0.0, 0.0, 0.0)	(0 0 1)[1 0 0]
bright green	(0.0, 45.0, 0.0)	(0 1 1)[1 0 0]
olive	(0.0, 18.0, 0.0)	(0 9 28)[1 0 0]
olive yellow	(0.0, 72.0, 0.0)	(0 28 9)[1 0 0]



750 μm in length

Rot. Cube grains below delamination

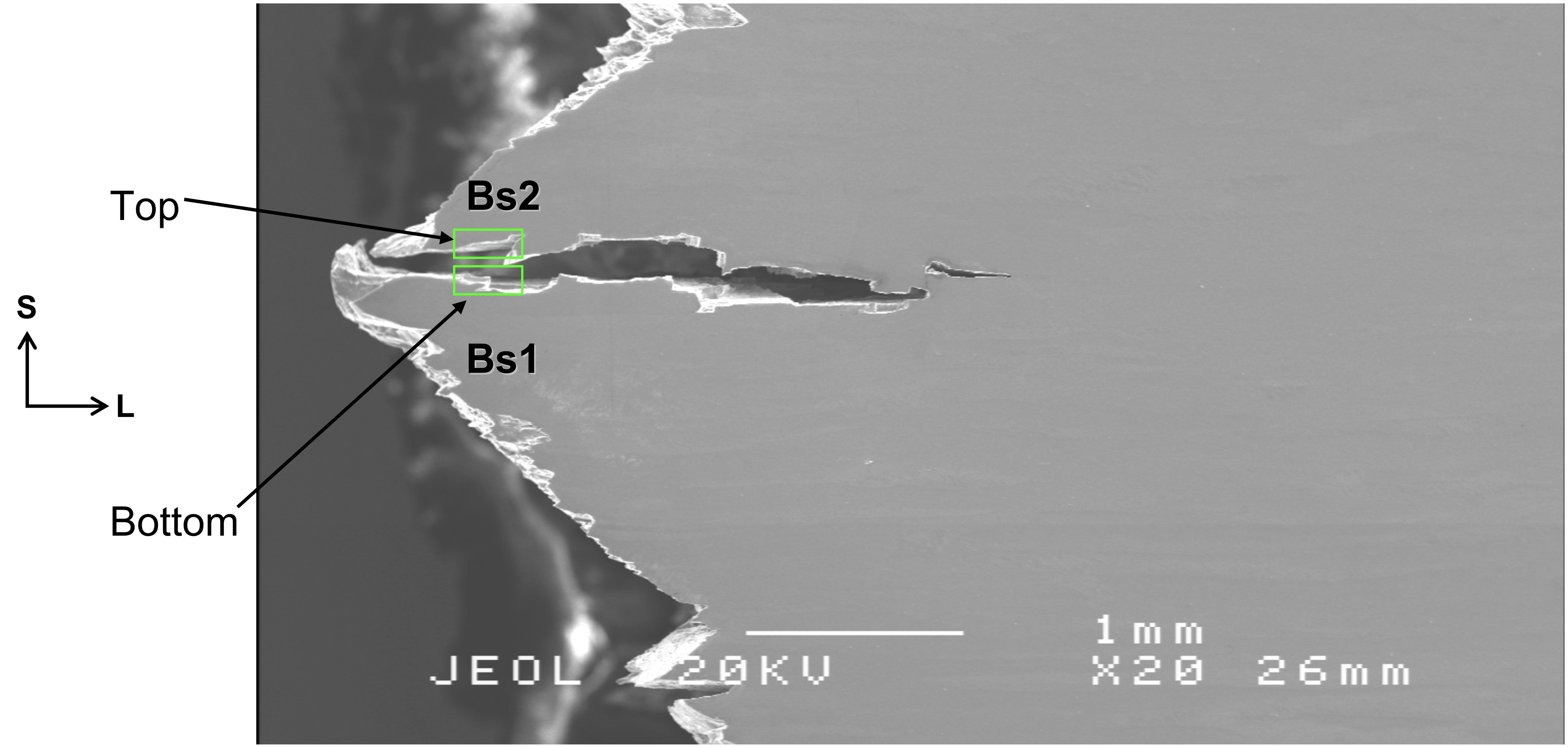
- Heavy damage accumulation

Typical fracture between **Bs1/ Bs2**

Delamination 2

Delaminations more often along Bs1/Bs2
Sometimes along Bs/Cube

Section of C458 L-T Fracture Toughness Sample



Images from boxed regions shown on following slides, tilted ±45° to view inner surfaces of delamination

C458 L-T Delamination Fracture Morphology

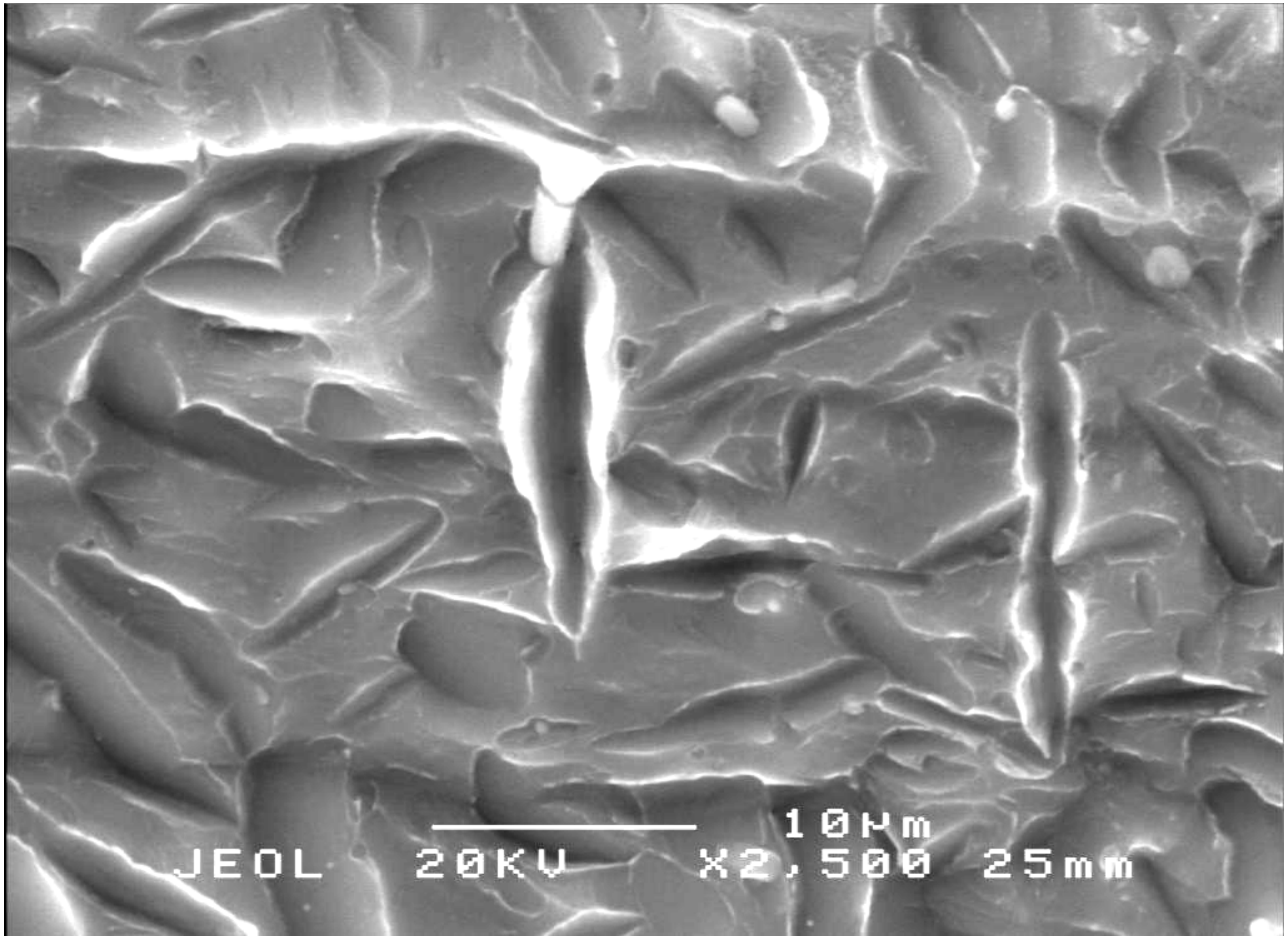
Top Side; Bs2

No slip offsets

wedge-shaped features

T

L



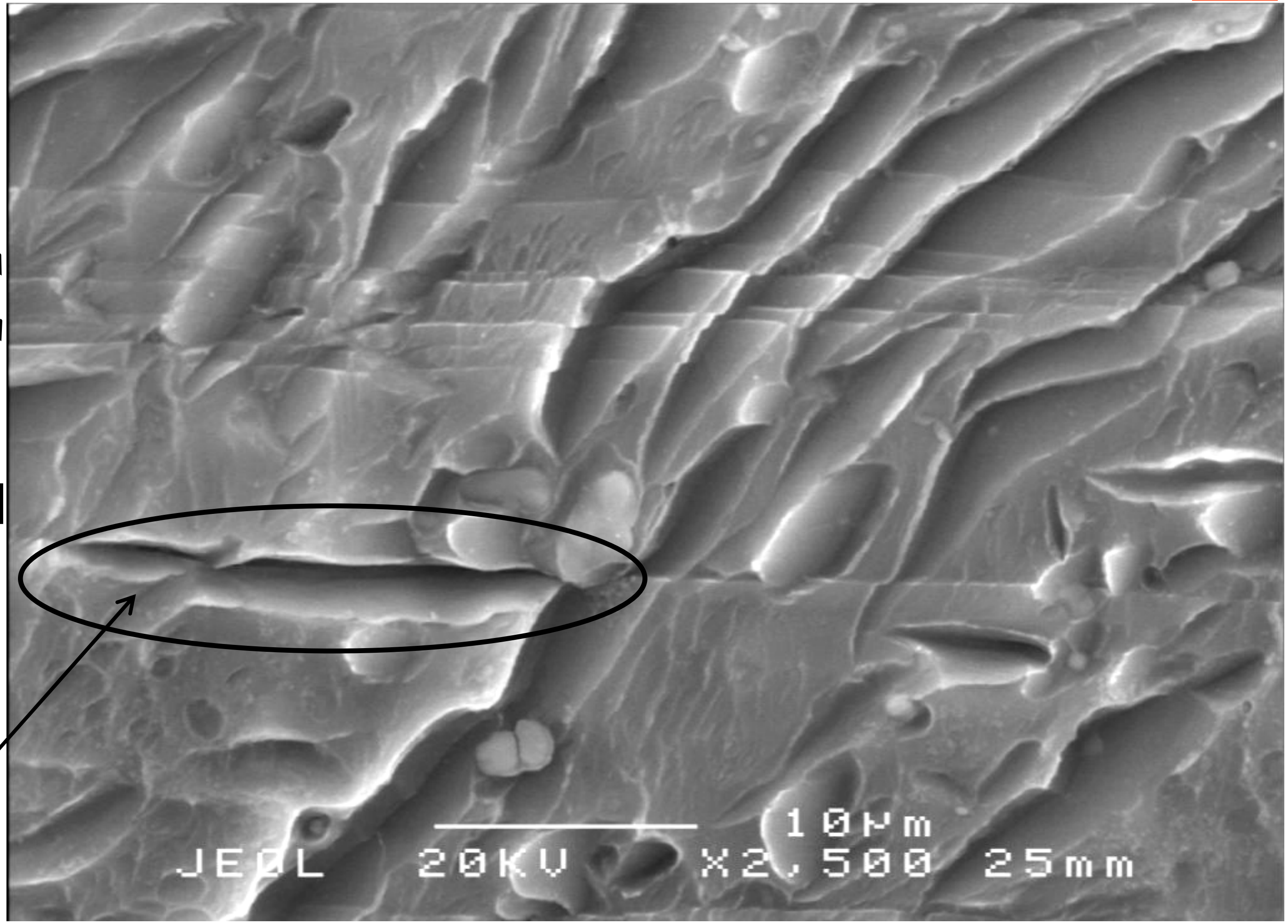
Involvement of grain boundary precipitates

C458 L-T Delamination Fracture Morphology

Bottom Side; Bs1

A

polished surface



Slip offsets

T

L [2 $\bar{1}$ 1]

Load axis

wedge-shaped features

Slip band offsets on one side, single slip plane, high stress concentration

(*slip bands parallel to load axis! Resolved shear stress for load direction = 0)*

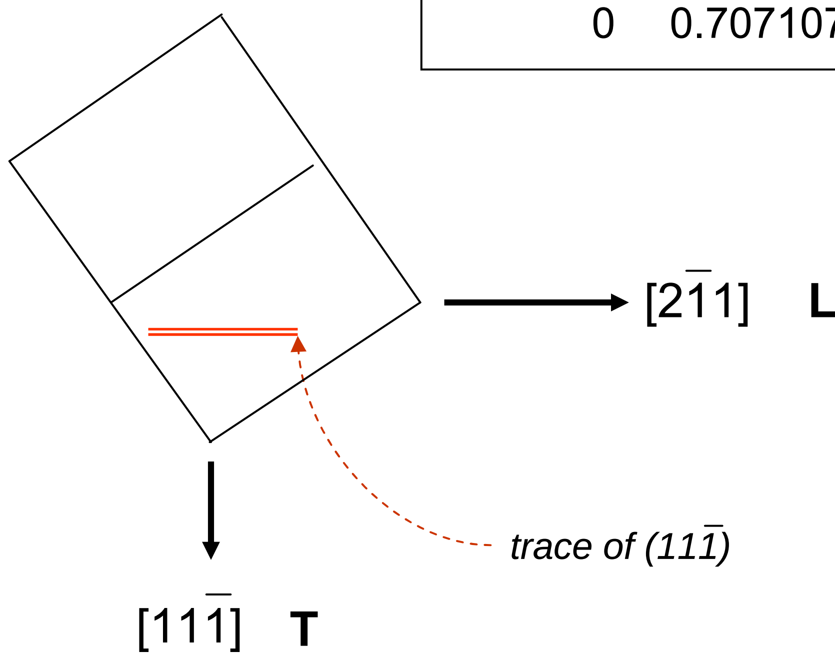
Schematic of slip band traces for A

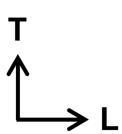
Bs1

rotation matrix

0.819152	-0.40558	0.40558	L
0.573576	0.579228	-0.57923	T
0	0.707107	0.707107	N

$(011)[2\bar{1}1]$





Resolved shear stress = 0
For L, T or N uniaxial loading

Crystallographic Selection of Delamination

- Results show preference for Bs1/Bs2, but why?
- Shear required for slip bands in $\boxed{A}$
- UIUC/NASA-MSFC/Alcoa collaboration:
  - Normal-shear coupling under plane stress conditions arising from plastic anisotropy provides driving force for delamination *after delamination initiation*
- **What if normal-shear coupling determines initiation sites?**
  - **Maximum** plastic anisotropy should be evident from the ***maximum difference*** in grain specific Taylor factors (ΔTF) at grain boundaries calculated from EBSD data sets using OIM software

Normal-shear coupling: strain tensor

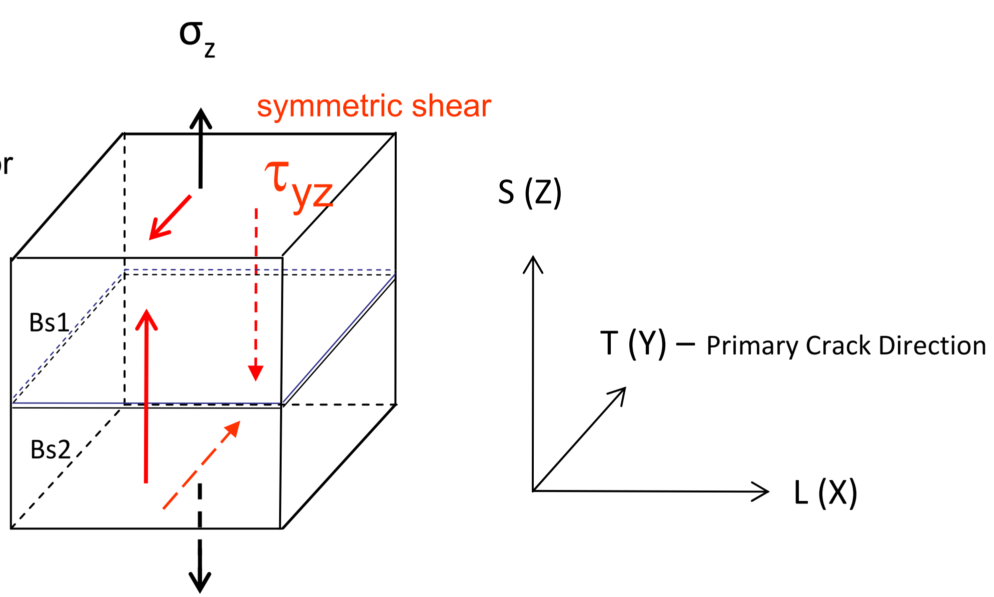
Deformation gradient: **F** = identity + strain tensors

$$\mathbf{F} = \mathbf{I} + \varepsilon = \begin{bmatrix} 1+\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{xy} & 1+\varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{xz} & \varepsilon_{yz} & 1+\varepsilon_{zz} \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 1 \\ 0 & 1 & 2 \end{bmatrix}$$

Diagonal strain components with the same subscript (i.e. ε_{xx}) represent normal strain components. All non-diagonal terms represent shear strain components.

Schematic of strain tensor

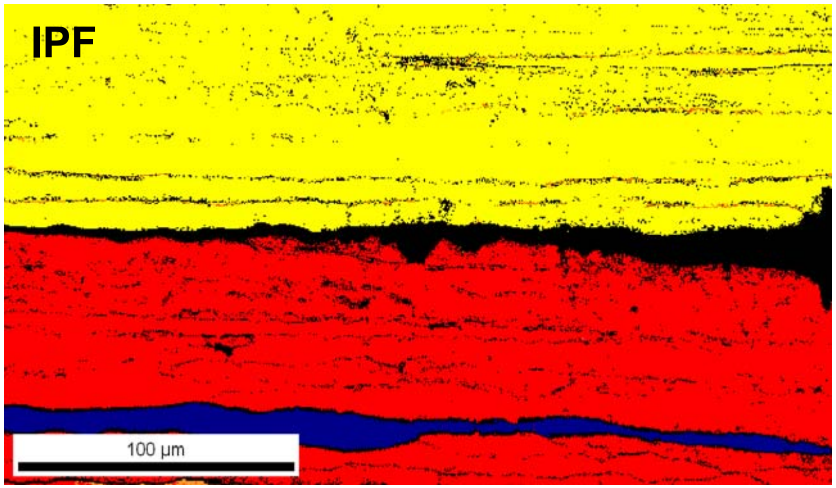
Delamination Boundary



Correlation Between Grain Orientation and
(n-s) Taylor Factor in 2090

Delamination 1

crack →



Grain Orientation, 20°

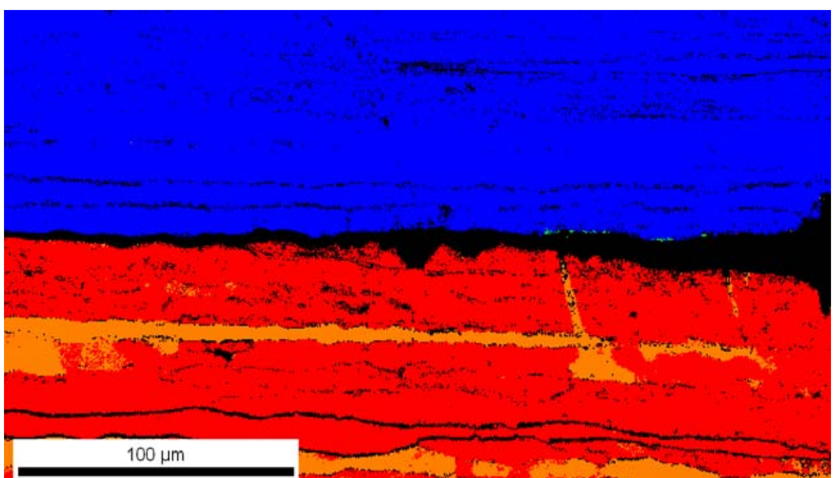
Orientation Euler Angles	Orientation {hk(i)l}<uv(t)w>
(35.0, 45.0, 0.0)	(0 1 1)[2 -1 1]
(55.0, 90.0, 45.0)	(1 1 0)[1 -1 2]
(39.2, 65.9, 26.6)	(1 2 1)[1 -1 1]
(90.0, 35.0, 45.0)	(1 1 2)[-1 -1 1]
(0.0, 0.0, 0.0)	(0 0 1)[1 0 0]
(0.0, 45.0, 0.0)	(0 1 1)[1 0 0]
(0.0, 18.0, 0.0)	(0 9 28)[1 0 0]
(0.0, 72.0, 0.0)	(0 28 9)[1 0 0]

S

L

1.5 mm long

crack →



Taylor Factor

Min	Max	Total Fraction
2.27532	2.54033	0.444
2.54033	2.80535	0.000
2.80535	3.07037	0.002
3.07037	3.33539	0.085
3.33539	3.60041	0.361

Correlation Between Grain Orientation and
(n-s) Taylor Factor in 2090

Delamination 2

Grain Orientation, 20°

crack

	Orientation Euler Angles	Orientation {hk(i)l}<uv(t)w>
yellow	(35.0, 45.0, 0.0)	(0 1 1)[2 -1 1]
red	(55.0, 90.0, 45.0)	(1 1 0)[1 -1 2]
orange	(39.2, 65.9, 26.6)	(1 2 1)[1 -1 1]
light orange	(90.0, 35.0, 45.0)	(1 1 2)[-1 -1 1]
green	(0.0, 0.0, 0.0)	(0 0 1)[1 0 0]
bright green	(0.0, 45.0, 0.0)	(0 1 1)[1 0 0]
olive	(0.0, 18.0, 0.0)	(0 9 28)[1 0 0]
yellow-olive	(0.0, 72.0, 0.0)	(0 28 9)[1 0 0]

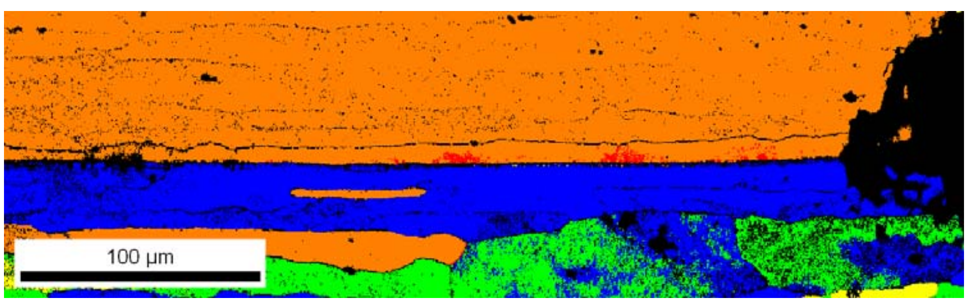
S

L

750 µm long

Taylor Factor

crack

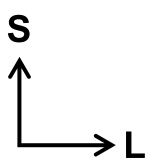


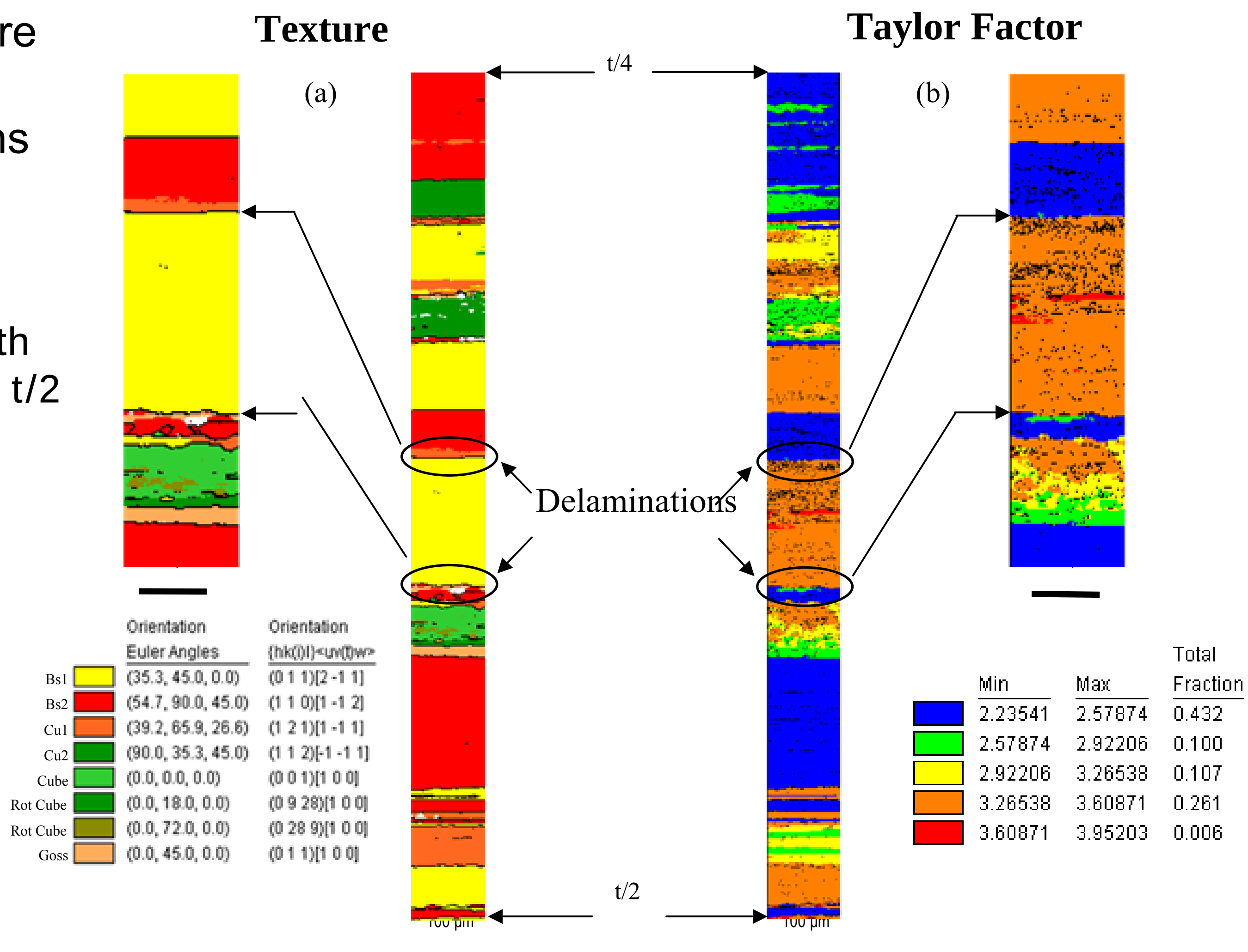
	Min	Max	Total Fraction
blue	2.28692	2.63136	0.216
green	2.63136	2.9758	0.104
yellow	2.9758	3.32025	0.012
orange	3.32025	3.66469	0.507
red	3.66469	4.00913	0.004

2090 Through-Thickness Texture and (n-s) Taylor Factors

Maps of microstructure **500μm past** delaminations

2mm depth
From t/4 to t/2

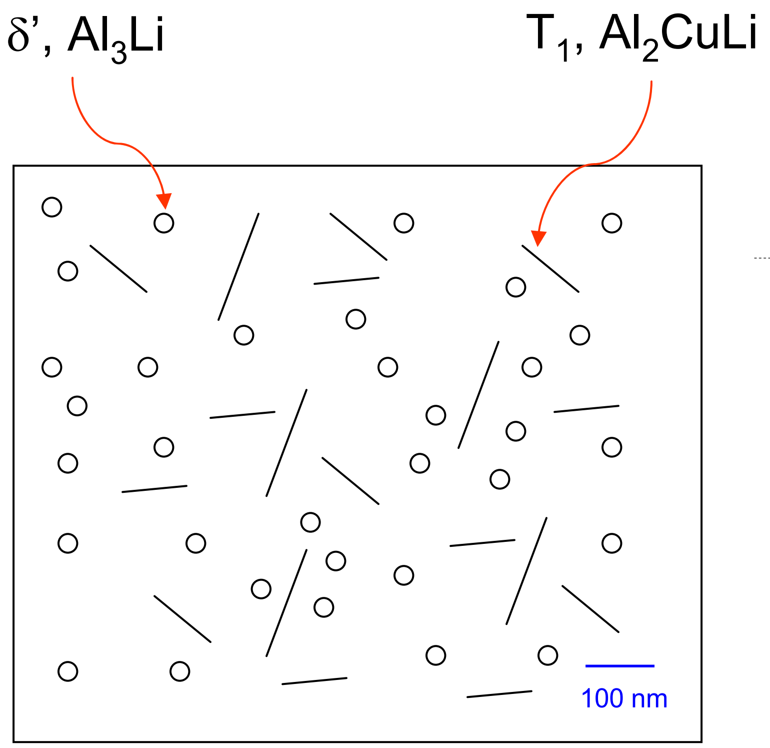


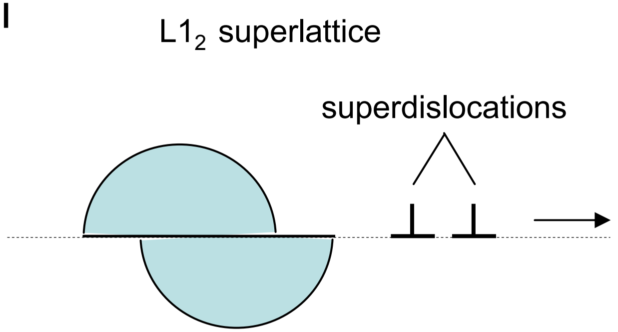


Delaminations between grains with the largest Δ TF
usually between Bs1 and Bs2.

Other factors

…shearing of ordered precipitates…planar slip





δ', shearing, reduced cross section

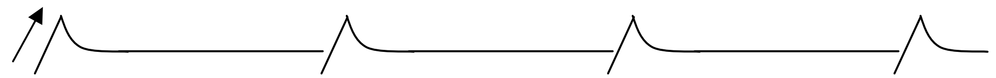
APD boundary between paired dislocations, cross-slip is impeded

Planar slip is enhanced

Other factors

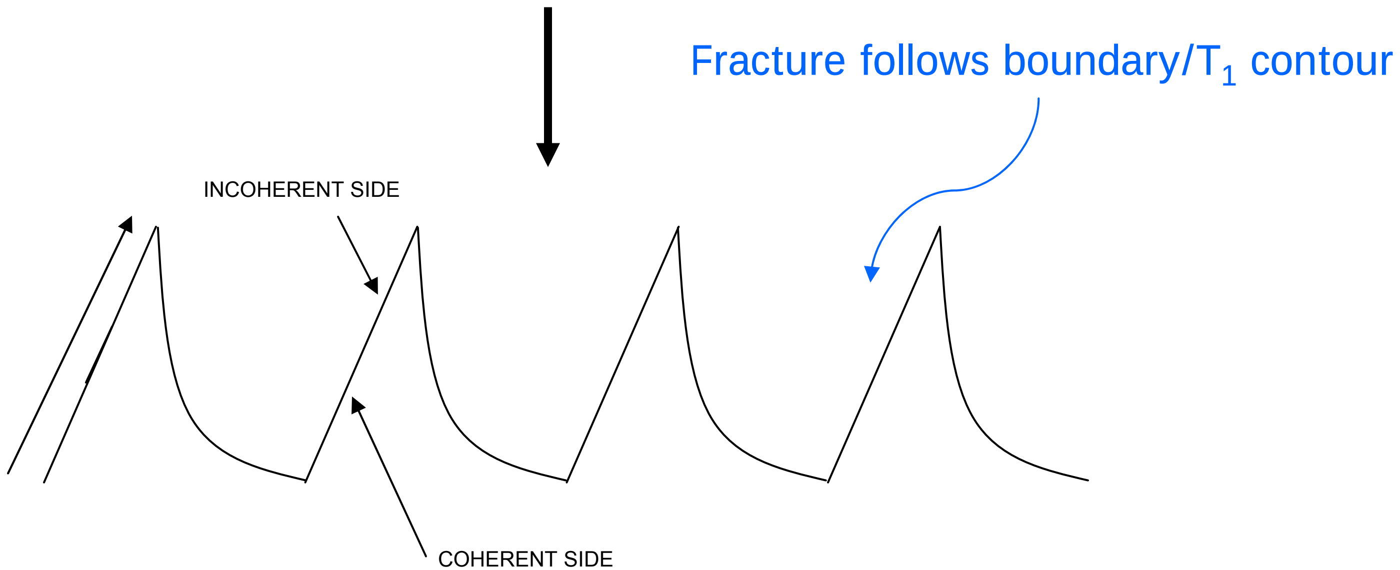
… semi-coherent grain boundary precipitates …

UA



GROWTH OF PLATES PULLS COHERENT INTERFACE AWAY FROM ORIGINAL GRAIN BOUNDARY PLANE

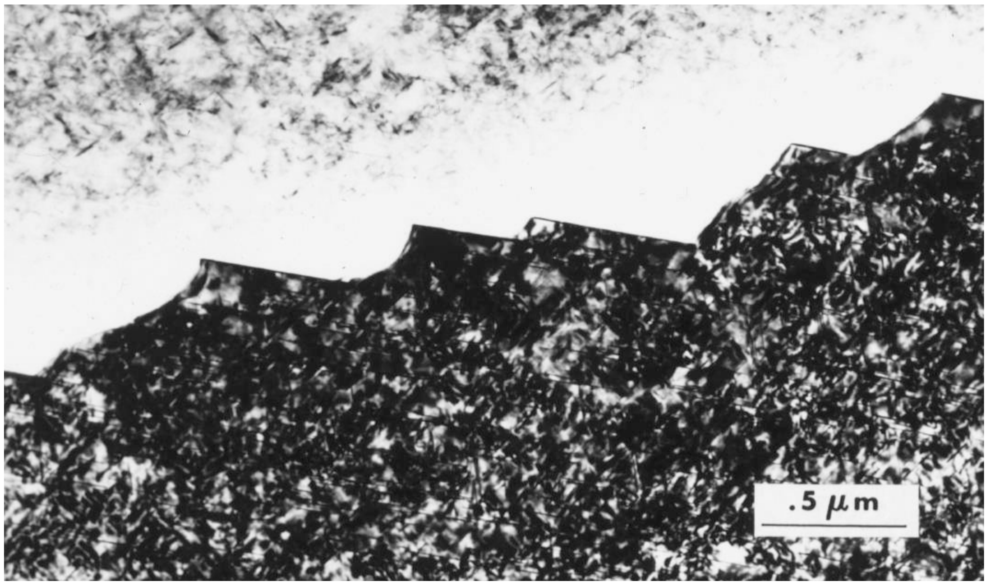
PA

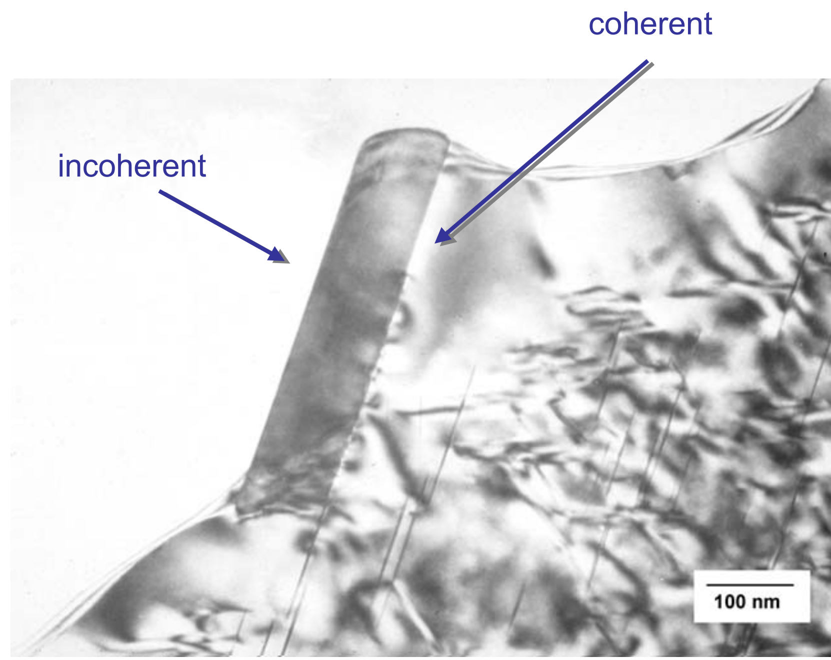


RECESS FEATURES ON DELAMINATION FRACTURE DUE TO DECOHESION OF T_1 PLATES
PLATE LENGTH 10 – 100 μm FOR BRASS GRAINS?

Transmission electron microscopy of T_1, Al_2CuLi, precipitates in 2090

LS Plane





incoherent, interphase boundary over most of grain boundary

TEM

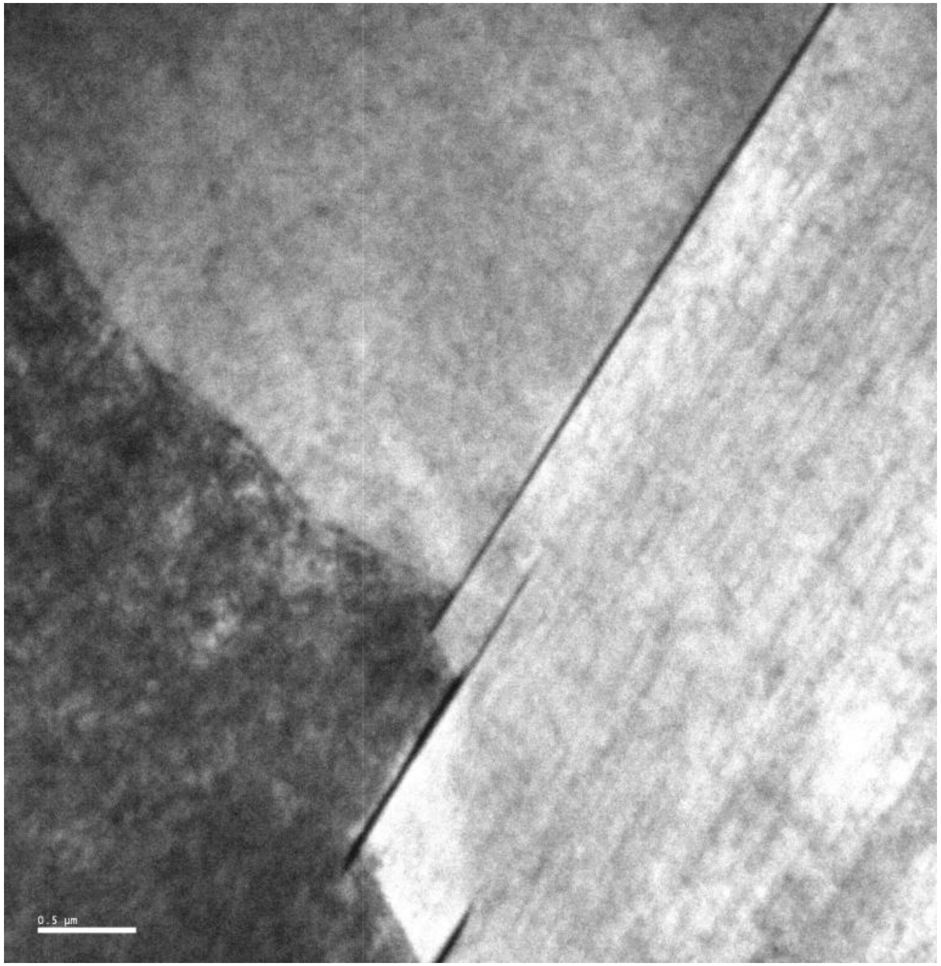
high magnification showing large T1plate and coherency strains on one side

TEM

{111} habit planes

2090 T8

Grain Boundary T_1 Precipitates in 2090



200 kV

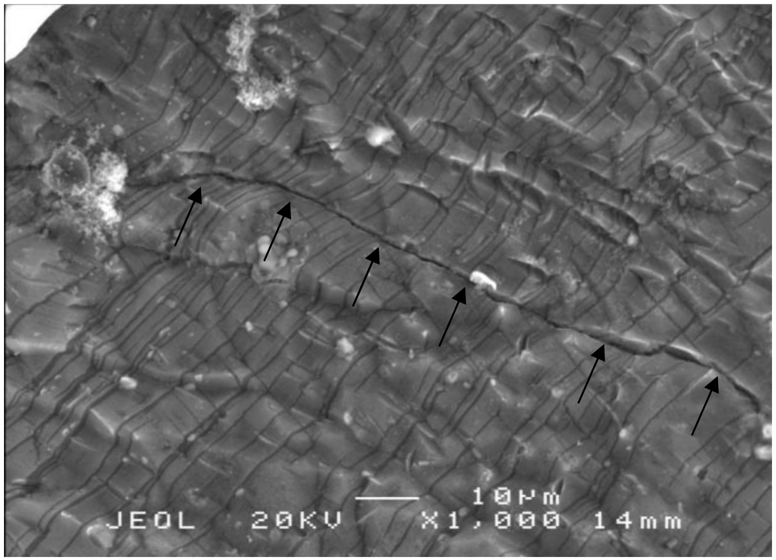
2090 T8 LS section
from thick region of sample

Electropolished,
Nitric:Methanol
1:3

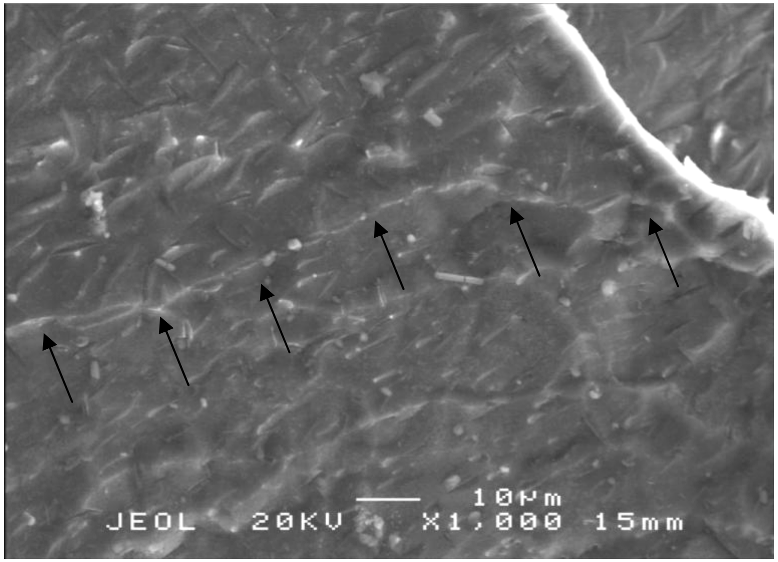
Some T_1 plates are several μm long, ~ 40 – 50 nm thick

C458 Strain anisotropy and orientation data from matching fracture halves:

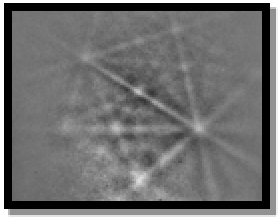
Bottom Half



Top Half

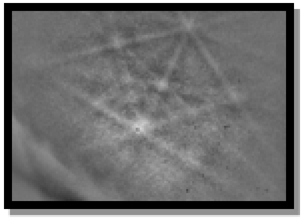


Wedge-shaped recesses.
Slip bands = high stress concentration



Cube

Wedge-shaped ridges.
No slip bands.



Brass

Diffraction from fracture surface!

Conclusions

- Crystal plasticity code finite element analysis predicts
  - Delaminations ahead of primary fracture
  - Anisotropic strain around delaminating boundary
  - Propagation under plane stress conditions *after* initiation, with normal-shear stress coupling

- OIM shows delaminations frequently at brass inter- variant boundaries

- For L-T compact tension tests, delaminations correspond to the largest (normal-shear-coupled) **ΔTF**

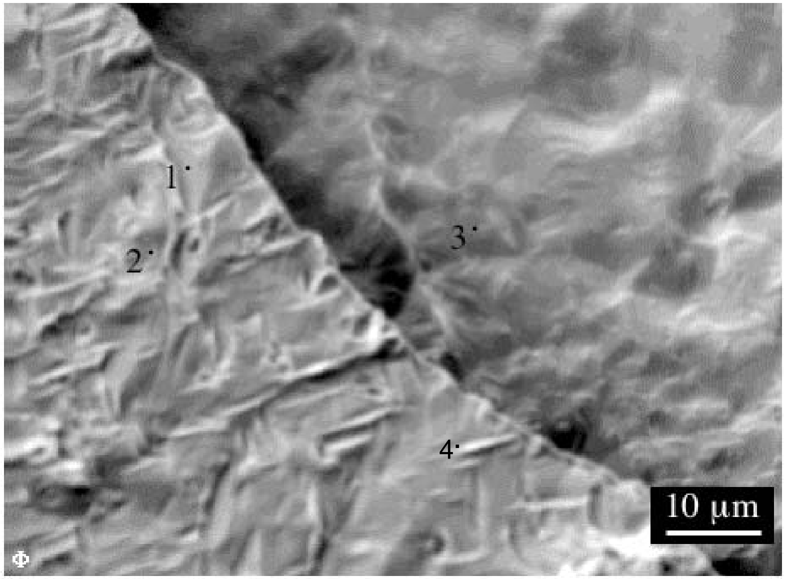
- Delamination fracture surfaces showed
  - One-sided (usually single) slip band formation = higher stress concentrations on one side of the fracture
  - T_1 precipitate decohesion

- Correlation of fracture features and orientation data possible

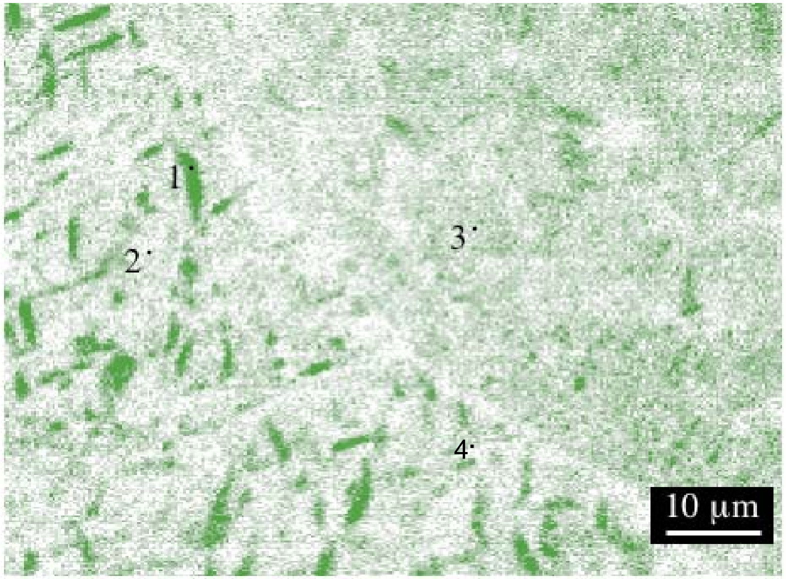
Scanning Auger Electron Microscopy

C458 in-situ **Fracture Surfaces**

Secondary Electron Image



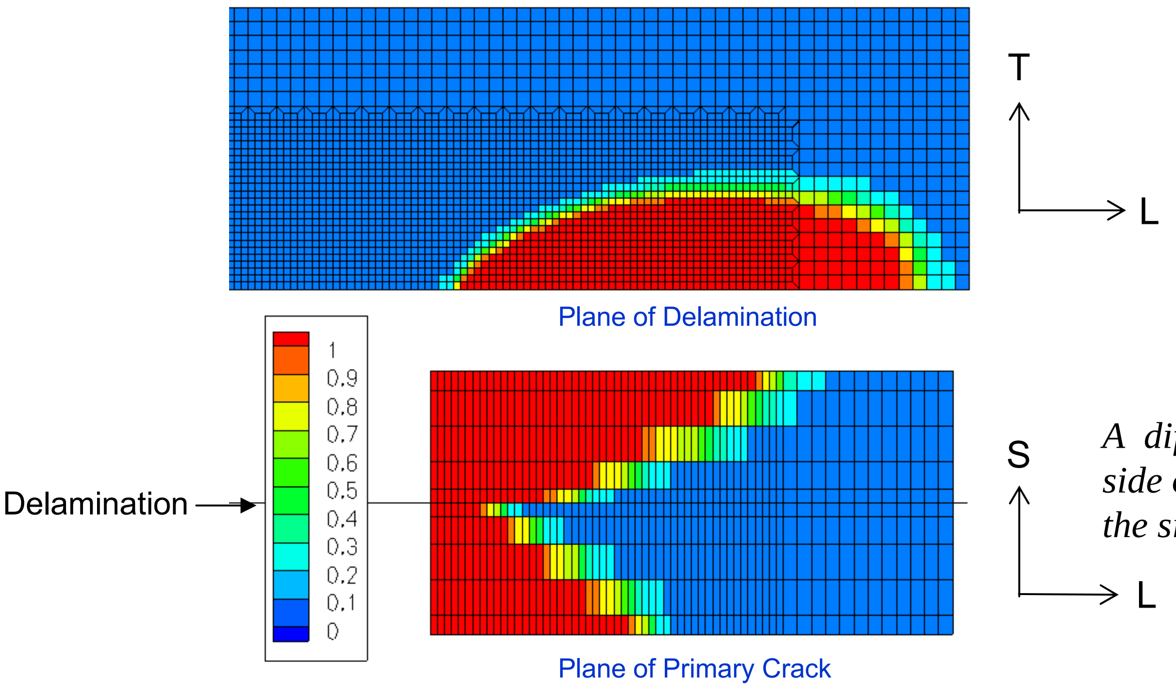
Auger Chemical Analysis
Green indicates Cu



*Images provided by Russell McDonald and Peter Kurath, UIUC

- Cu concentration at raised wedge-shaped features indicates T_1, Al_2CuLi precipitate plates
- Cu removed by 50 nm sputtering

T-L Fracture, FE Simulation Results
UIUC Crystal Plasticity Model using WARP3D*



Delamination occurs
For $\sigma_{primary}$ ≥ **5x** σ_{delam}

A difference in plastic activity on either side of the delamination is indicated by the simulation.

Primary crack propagation

Delamination occurs ahead of primary crack front
Primary crack grows asymmetrically, significant **plastic anisotropy** for Bs/Cu interface.

Normal-Shear stress coupling under **plane-stress** conditions *after* initiation

*incorporating the anisotropic plasticity yield surface model, Yld2004-18p (*Barlat et al., Int. J. Plas. 2005; 21: 1009-1039)* with cohesive zone elements